Imaging Spectrograph Based Spectral Imaging System

Hannu Laamanen[1], Timo Jaaskelainen[1], Markku Hauta-Kasari[2], Jussi Parkkinen[2], and Kimiyoshi Miyata[3]
[1]Department of Physics, [2]Department of Computer Science, University of Joensuu, Joensuu, Finland
[3]National Museum of Japanese History, Department of Museum Science, Chiba, Japan

Abstract

This paper gives a review of the work carried out in the field of spectral imaging at the University of Joensuu. First we describe a spectral imaging system constructed in the University of Joensuu during last year. The system uses a spectral camera composed of an imaging spectrograph coupled to a CCD B/W matrix camera and an XY-table for the object scanning. We also consider fundamental aspects of metameric color reproduction and we describe a simple method for image reproduction by using a CRT display or other additive devices. In the last part of this paper we give an example of one application: the spectral imaging and color reproduction of icons from the middle of the 19^{th} century.

Introduction

During recent years spectral imaging has gained a growing attention in applications like remote sensing and medical-imaging etc. and it has propagated into new application areas where trichromatic imaging is traditionally used. Also many different devices are already commercially available. There are four different techniques or system types: narrow band grating systems, broad band grating type systems, acousto-optic tunable filter systems, and (interference) filter wheel systems. In this paper we present an imaging spectrograph based system, that is a narrow band grating system.

One application area of spectral imaging is digital archiving of art works like paintings. In addition to the spectral imaging of an object, also color and image reproduction of the original object is essential part of this application. This is why we consider also some primary aspects of color reproduction in this paper.

Spectral Imaging System

The system uses a spectral camera composed of the ImSpector V8 direct sight imaging spectrograph[1] coupled to the PixelFly 230XS 1525 (540SC 0335) B/W CCD camera. Canon 50 mm photographic lens is used as a primary imaging objective. Spectral camera captures a line image and uses two prisms and a grating to disperse it to a spectrum in a direction opposite to the line direction, shown in Fig. 1. Spatial information is gathered in the line direction. This results to one-dimensional spectral image (two-dimensional gray level image) that consists of 1280 pixels in spatial dimension (line direction) and 1024 pixels in the spectral dimension (perpendicular to line direction). So full spectral information of each pixel in the line image is obtained by one direct measurement. The final two-dimensional spectral image, which is a three-dimensional data cube with one spectral and with two spatial dimensions, is obtained by spatially scanning the object in the direction perpendicular to the line direction.

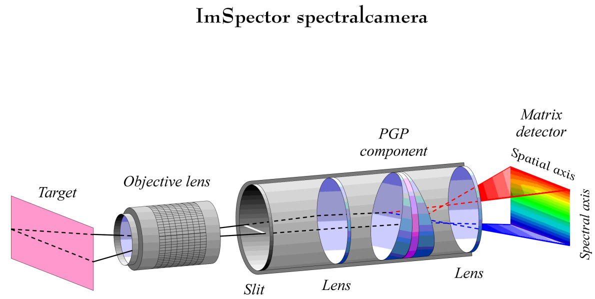

Figure 1. Schematic of the spectral camera.

Spectral range of the camera is from 380 nm to 780 nm and spectral resolution 4 nm, but normally data is interpolated to have 5 nm or 10 nm intervals, which results to 81 or 41 wavelength channels. Responses of neighbor pixels are usually coupled in spatial direction for decreasing noise level. Sample reflectance can be separated from the system response by taking a pixel by pixel ratio of sample image to the image of white reference sample:

$$R_{xy} = \frac{sample_{xy} - dark_{xy}}{white_{xy} - dark_{xy}} \qquad (1)$$

This also corrects the spatial non-uniformity of lighting.

For scanning and moving an object or the camera there were used two step motor guided ball screw driven slides. Slides were crossed together to form an XY-table. The largest movements in X- and Y-directions are both 120 cm, which set the maximum size for the object. Smallest step sizes in X- and Y-directions are 25 µm and 50 µm respectively. At the moment a lens used for the system and the optics of the camera sets the maximum for the spatial resolution, which is about 0.4 mm in scanning direction and 40 µm in opposite direction.

Because imaging spectrograph shares white light into spectrum, a higher light power level is required if compared to trichromatic imaging. In this system the object is illuminated in 45° to its surface by Spectralight III daylight simulator, which is a filtered halogen lamp. It is not necessary to illuminate the whole sample area at the same time, but only the area of the scanning line, so line lighting would be ideal choice for this kind of system. An illuminator should produce enough light power trough the whole visible spectrum with no sharp peaks, thus fluorescence lamps cannot be used.

Figure 2. Spectral imaging system. A is illuminator, B is spectral camera, C is XY-table, and D is sample holder.

Repeatability of measurements was tested so that MacBeth ColorChecker was measured 20 times, with about 120 measurement points or pixels in each single color area. Altogether there were 61440 color measurements, 3072 samples each measured 20 times. 20 point-wise measured values were compared with the mean value of the measurements. The measurement error was defined as a difference between a single measurement and the mean value. The result was such that the average ΔE^*_{94} color difference of 61440 color measurements was 0.13 and the standard deviation and the maximum of the all color differences were 0.11 and 5.0 respectively.

It takes about 11 minutes to scan A4-size paper with 0.4 mm resolution and with 115 ms exposure time. Because in this case the total exposure time is almost 6 minutes, system's speed could be increased by using a brighter illuminator.

Metameric Color Reproduction

In this section we describe a method for color and image reproduction by using a CRT display. Here we have focused on CRT display, but the same method can be used with other devices that comply with laws of additive mixing, such as most LCD displays, projectors etc.

Display Characterisation

Device characterization means determining the relationship between device coordinates and the colorimetric coordinates.

A physical model for a CRT display involves two steps: a nonlinear transformation between drive voltages in the digital-to-analog converter (DAC-values) and corresponding phosphor luminances and a linear transformation between phosphor luminances and corresponding XYZ tristimulus values. In the case of CRT displays Gain-Offset-Gamma model (GOG-model) is normally used to model nonlinear part of the transformation. With other devices it is more preferable to use interpolation of 1D-lookup tables (LUTs) instead of the GOG-model.

Instead of using actual luminance or radiance levels it is more common to use scalars called monitor tristimulus values R, G, and B. They are computed using the spectral radiance of red, green, and blue channels at maximum excitation $L_{\lambda,r,\max}$, $L_{\lambda,g,\max}$, $L_{\lambda,b,\max}$ as primaries. In the GOG-model the nonlinear relationship between RGB and DAC-values d_r, d_g, and d_b is defined by following equations:

$$R(d_r) = \left[k_{g,r}\left(\frac{d_r}{2^N - 1}\right) + k_{o,r} \right]^{\gamma_r} \tag{2}$$

$$G(d_g) = \left[k_{g,g}\left(\frac{d_g}{2^N - 1}\right) + k_{o,g} \right]^{\gamma_g} \tag{3}$$

$$B(d_b) = \left[k_{g,b}\left(\frac{d_b}{2^N - 1}\right) + k_{o,b} \right]^{\gamma_b}. \tag{4}$$

Coefficients k_g, k_o, and γ represent model's gain, offset and gamma nonlinearity, respectively. N is DAC quantization depth.

Next equation defines the connection between RGB scalar values and XYZ tristimulus values of color sample on display.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{offset} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{refl.} \tag{5}$$

Matrix elements $X_{r,,\max}$, $Y_{r,\max}$, and $Z_{r,\max}$ are CIE1931 tristimulus values of $L_{\lambda,r,\max}$. Two last vectors in equation represents the display's offset and the reflection of the external light from the surface of display screen. When GOG-model is used the offset term is normally excluded from equation (5), because equations (2) – (4) already include offset coefficients.

A more complete description of the characterization of color CRT displays is given by Berns et al[2].

Practical Implementation

CRT display characterization requires spectroradiometric or colorimetric measurements of light emitted by phosphors. A color ramp is measured separately for each primary color channel in order to derive the RGB-to-XYZ transformation and the nonlinear transfer function for each primary color channel. The DAC value of measured color channel is increased from zero to its maximum with suitable steps, while other DAC values are kept zeros. The color spectrum of each DAC combination is measured. Also black (d_r=0,d_g=0,d_b=0) and white (d_r=1,d_g=1,d_b=1) colors are measured. All measurements are done in a darkened room or laboratory. A plot of the CRT primary color ramps is shown in figure 3.

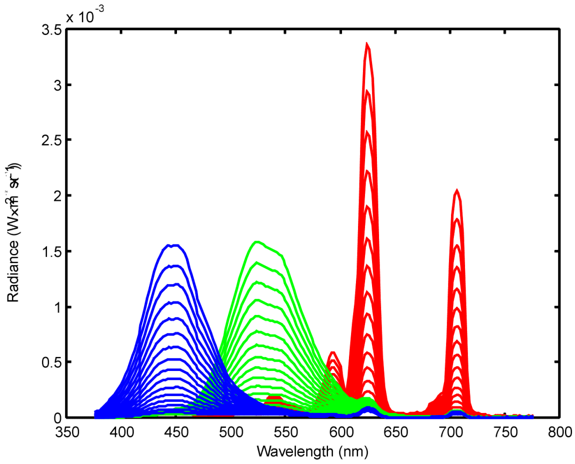

Figure 3. CRT primary color ramps.

The spectral data of each color ramp is changed into the format of XYZ tristimulus values. XYZ values corresponding DAC-values (0, 0, 0) forms the offset term in equation (5). Then the same offset term is subtracted from every other measurement. Matrix elements $X_{r,,max}$, $Y_{r,max}$, and $Z_{r,max}$ are XYZ tristimulus values corresponding red channels maximum DAC values (1, 0, 0), and similarly for green and blue channel. R, G, and B values of each measurement are defined by equations

$$R = X_r / X_{r,\max} \quad (6)$$

$$G = Y_g / Y_{g,\max} \quad (7)$$

$$B = Z_b / Z_{b,\max} . \quad (8)$$

A plot of R as a function of d_r represents so called gamma curve of the red color channel. Now each point of that curve can be calculated by interpolating measured data or by fitting equation (2) in it.

Color Reproduction

When original object and its reproduction are observed side by side, monitors color temperature should match nearly with prevailing illumination and monitors maximum luminance level should be slightly higher. We also assume that the spectral image of the object and the illumination spectrum are already measured. A reflection of light from the surface of screen is measured and the reflection term is set into Eq. (5). Also the luminance level is defined from that point where object stands and measured illumination spectrum is multiplied with such coefficient that it results to same luminance level.

Now each spectrum in the spectral image is multiplied with the scaled illumination spectrum and with the color-matching functions. The spectral image is changed to XYZ-image. Then R, G, and B are solved from Eq. (5) and it is implemented separately to each pixel of the XYZ-image. Finally DAC-values are achieved by using interpolation of 1D LUTs or by using Eq. (2) – (4).

Applications

The system was applied for taking spectral images of skin samples and also for measuring different type of printed samples and art works like paintings. Here we describe the latter case in more detail.

Measurement of Historical Objects

As an application, the developed measurement system was used to measure the spectral reflectance of icons, which are suitable example of historical objects. Figure 4 shows an example of the icons. Overall ten icons were measured by the system described earlier in this paper. These icons were painted on wooden plate by using natural pigments.

The size of these icons is about H:240 mm x W:165 mm at the minimum and H:430 mm x W:330 mm at the maximum.

Figure 4. An example of measured icons.

Setup of Measurement

Each icon was placed on the sample holder of the measurement system perpendicular to the spectral camera. The light source was D65 equivalent illuminant, and the lighting direction was about 45 degree to the icon surface.

Because the width of field to be measured is narrower than the width of the icon, each icon was measured by divided into several stripes. The number of stripes required to measure the whole icon depends on the size of the icon, but the width of each stripe was identical for the all icons and its value was 67.6 mm on the surface of the icon. The resolution of the measurement was 0.42 mm by 0.42 mm on the surface of the icon.

Some icons had non-flat surface. If the icon had a curved surface in the horizontal direction, the icon was placed in the vertical and horizontal direction, then measured twice. If the icon had a concavity structure, the icon was also turned upside down to avoid unwanted effect of its shadow.

Results of Measurement

The measured stripes in each icon were merged to make whole spectral reflectance image. After that, the merged spectral reflectance images were used to calculate RGB digital images to reproduce the icons on a CRT computer monitor with high accurate color reproduction. The spectral reflectance images were also used to simulate color reproduction of the icons under different illuminants, e.g. standard A-illuminant or equi-energy white illuminant.

The principal component analysis method[3] and k-means clustering method[4] were applied to investigate basic characteristics about the measured spectral reflectance image of the icons. Furthermore, the spectral reflectance images were also used to investigate what kind of and how many pigments were used in each icon. In addition to this, the color pairs, which have the same tristimulus value but different spectral reflectance, were searched. These color pairs are metameric colors for each other in the icon. The metameric color pairs could be considered as a candidate area to show where some colors were repainted after the icon had painted. In the historical objects, this kind of information could be useful to know about the history of the objects.

The application of the measurement system has just been started. The system has an advantage to measure the spectral reflectance of an object without any estimation techniques of the spectral reflectance. The investigations based on the measured spectral reflectance images are now in progress with this advantage. The detailed results of the investigations will be presented in the future.

Conclusion

We presented a spectral imaging system based on a direct sight imaging spectrograph. System's advantages are that it measures spectral reflectance data directly without the use of estimation techniques and image size is set by the object and pixel size, not by the maximum resolution of the CCD like in other system types. On the other hand the object is spatially scanned, so a longer time is required for measuring larger objects. The system was applied for taking spectral images of skin samples and also for measuring different type of printed samples and art works like paintings.

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Biography

Hannu Laamanen received his M.Sc. degree in physics from the University of Joensuu, Finland in 1999. Currently he is a Ph.D. student at the University of Joensuu. His research focuses on spectral color and image analysis.